Parameterizing the Effects of Upper-Ocean Large Eddies on Air-Sea Interaction

Ming Li
Horn Point Laboratory
University of Maryland Center for Environmental Science
2020 Horn Point Road, Cambridge, MD 21613
Phone: 410-228 8420, Fax: 410-228 8490
Email: mingli@hpl.umces.edu

Chris Garrett
School of Earth and Ocean Sciences
University of Victoria
P.O. Box 3055, Victoria, B.C. Canada, V8W 3P6
Phone: 250-721 7702, Fax: 250-721 7715
Email: garrett@phastf.phys.uvic.ca

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LONG-TERM GOALS

To understand the effects of upper-ocean turbulent processes on air-sea interaction and obtain improved parameterization of these processes for use in large-scale ocean models.

OBJECTIVES

There are two primary objectives in this CBLAST modeling project. First, we seek to understand the dynamics of upper-ocean large eddies which play a critical role in the air-sea exchange and obtain physics-based parameterizations of momentum, energy and heat fluxes in the ocean surface boundary layer. Second, we seek to understand and interpret upper-ocean measurements acquired during the CBLAST low and hurricane field experiments.

APPROACH

Our approach is to combine process-oriented numerical modeling studies in nondimensional parameter space with simulations and interpretations of upper-ocean data obtained from the CBLAST field programs. Our primary modeling tool is the Large Eddy Simulation (LES) model, but we shall consider other analytic or numerical models that may be better suited for processes such as bubble dynamics and horizontal variability of the upper ocean at low-wind conditions.

In process studies, we initially make simplifications and consider idealized problems. We shall identify a set of controlling nondimensional parameters which can describe a whole range of wind speeds, surface wave fields and thermal forcing conditions. We then explore the model results in this parameter space and attempt to rationalize the results in terms of physical principles. By doing this, we hope to see the dynamic processes in perspective and develop robust parameterization schemes.

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In data simulations, we shall collaborate with the field investigators conducting both CBLAST low and hurricane experiments. Main CBLAST-Low experiments take place during FY02 and FY03. The hurricane field investigators plan to conduct experiments during the hurricane season between FY02 and FY04. Given these time frames, we plan to focus on process-oriented studies in FY02, work with the low-wind investigators in FY03 and FY04 and with hurricane investigators in FY04 and FY05.

WORK COMPLETED

We have configured the LES model to run on the PC platform so that multiple LES runs can be done simultaneously on a host of dual-processor PC workstations. This is useful as we need to explore the parameter space in process studies. We have also adapted the LES model to run hindcast simulations. We tested the model simulations using the observational data collected from a research cruise in the North Pacific. This helps prepare us to run simulation studies for the CBLAST experiments.

A major part of CBLAST-Low experiment is conducted in a shallow-water environment near Martha's Vineyard Coastal Laboratory. Although CBLAST focuses on turbulent processes associated with the air-sea interaction, turbulence generated in a tidal bottom boundary layer could complicate the interpretations of turbulence flux measurements in the water column. In order to discern the effect of the bottom-generated turbulence, we have added a tidal forcing term in the LES equations. We parameterize the effects of the bottom boundary by specifying a bottom Reynolds stress distribution in accordance with the law of wall scaling. Low-order turbulence statistics obtained from the modified LES model, including the boundary-layer depth and profiles of velocity variances, momentum flux and eddy viscosity, agrees well with known observations of tidal boundary layers. This model development will help interpret tower measurements obtained by the CBLAST-Low investigators.

RESULTS

Wave-driven Langmuir circulation, buoyancy-driven thermal convection and shear-driven Kelvin-Helmholtz billows are the dominant large eddies in the ocean surface boundary layer. As a part of the process studies, we are examining how they compete to generate turbulence in an initially well-mixed layer. By nondimensionalizing the LES equations, we have identified two controlling dimensionless numbers: (1) Hoenikker number Ho (Li & Garrett, 1995, JPO) is a ratio of buoyancy force to vortex force; (2) turbulent Langmuir number La_t (McWilliams et al. 1997, JFM) is a ratio of the water friction velocity to the Stokes drift velocity. Skyllingstad & Denbo (1995, JGR) and McWilliams et al. (1997) examined these turbulent flows in their LES simulations, but did not explore the parameter space. Here we carry out a systematic investigation into the dynamics of the large eddies in $La_t – Ho$ parameter space.

Figure 1 shows a comparison between three LES runs: (a) Langmuir circulation plus surface heating; (b) Langmuir circulation without surface heat flux; (c) Langmuir circulation plus surface cooling. Langmuir circulation represents a moderate wind speed of 8 ms^{-1} and a surface wave field with the dominant wave length of 30 m and wave height of 1 m. A surface heat gain of 600 Wm^{-2} is added for the heating case while a heat loss of –200 Wm^{-2} is added for the cooling case. The corresponding nondimensional parameter values are noted in the figure caption. While previous 2D DNS studies by Li & Garrett (1995) suggest little difference in the flow dynamics at these small values of Ho number, the 3D LES simulations reveal significant differences in the vertical velocity field, particularly at lower depths. Surface heating inhibits the vertical penetration of Langmuir cells, whereas downwelling plumes penetrate deeper when the water is cooled at the surface.

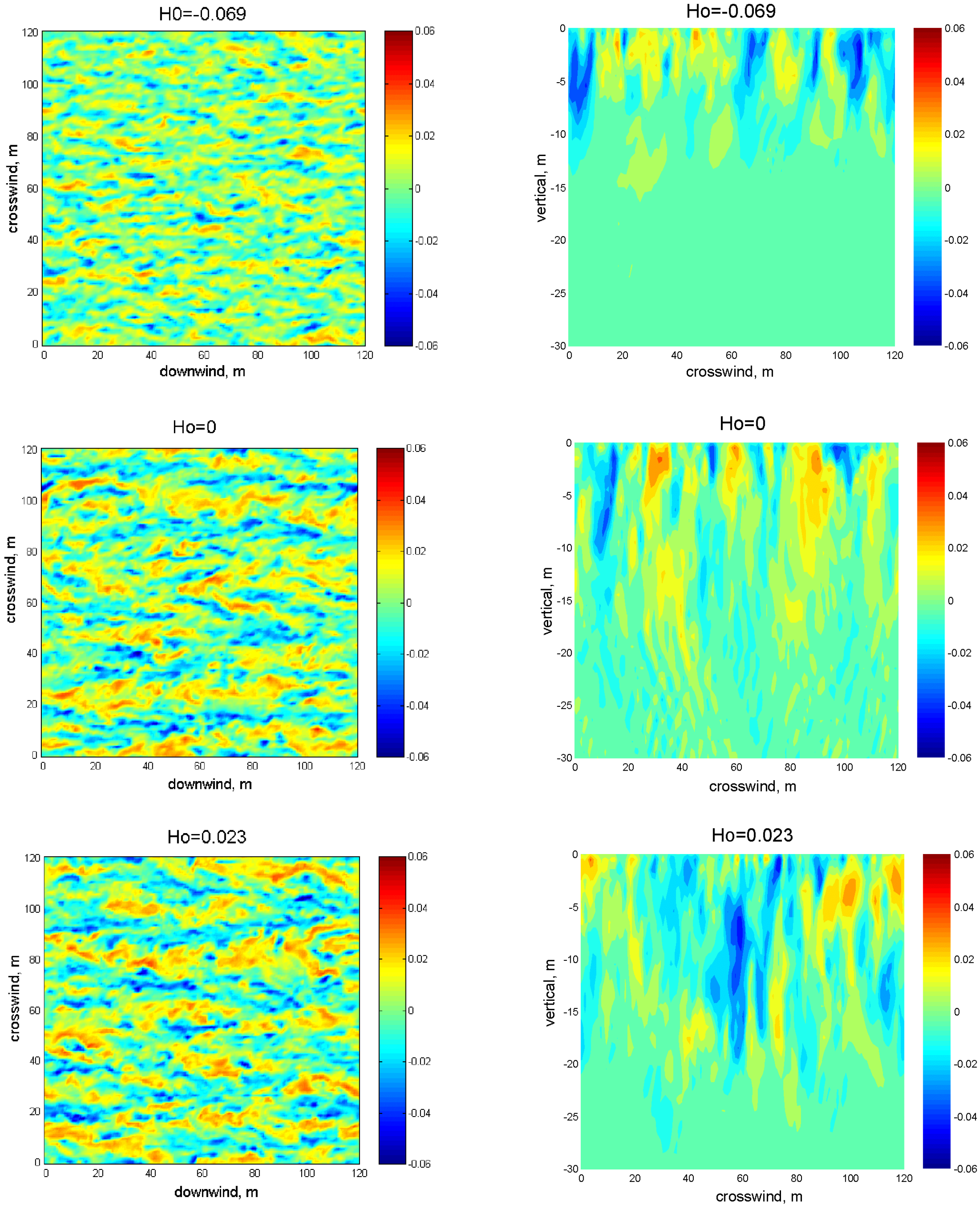

Figure 1. LES simulations of Langmuir turbulence with different combinations of surface heat fluxes. The middle row corresponds to Langmuir turbulence at a moderate wind speed of 8 ms^{-1}. This corresponds to La$_t$=0.36. The top row corresponds to Langmuir turbulence with surface heating of 600 Wm^{-2} (Ho=-0.068), whereas the bottom row corresponds to Langmuir turbulence with surface cooling of -200 Wm^{-2}(Ho=0.023). The left column shows the vertical velocity distributions at a horizontal plane 3 m below the sea surface. The right column shows the vertical velocity distributions at a vertical section perpendicular to the wind direction.

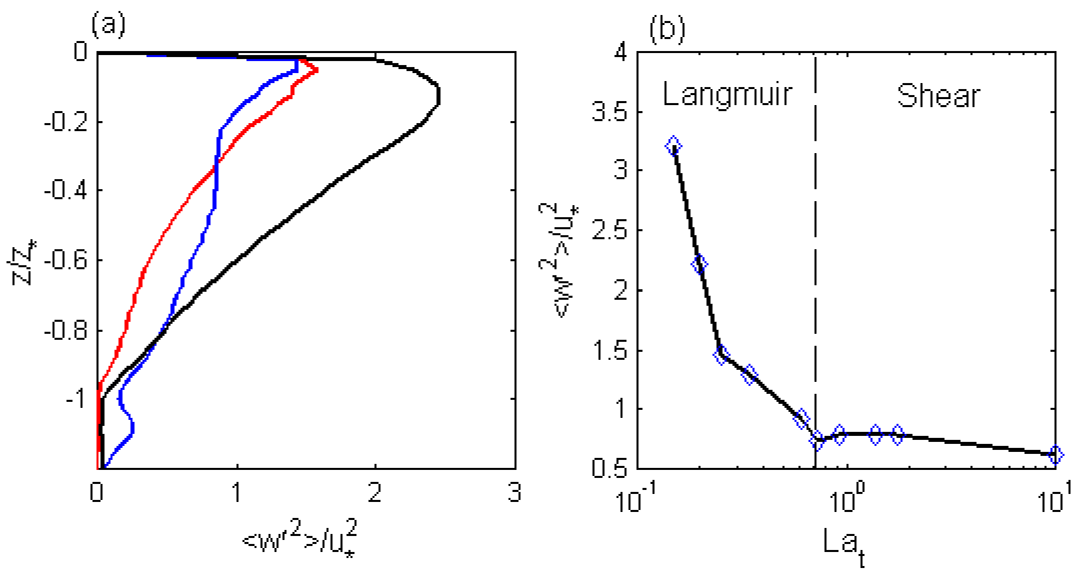

Figure 2. Transition from shear-dominated to Langmuir-dominated turbulence. (a) Profiles of vertical velocity variances at $La_t = \infty$ (red line), La_t=0.73(blue line) and La_t=0.34 (black line). z_* =40 m is the mixed-layer depth and u_* is the water friction velocity. (b) Depth-averaged vertical velocity variances as a function of La_t. The rightmost point corresponds to a pure shear turbulence with $La_t = \infty$ but is plotted in this way for visual presentation. All runs starts with a homogeneous layer down to a depth of 40 m and a linearly stratified thermocline with a thickness of 10 m and a buoyancy frequency of 0.008 s^{-1}. All LES simulations are run to a quasi-equilibrium state and the lower-order statistics are extracted by averaging the turbulence field during this period. No significant entrainment was observed at the base of the surface mixed layer over the model integration time.

We have also explored the transition from shear-dominated turbulence to Langmuir-dominated turbulence in the absence of surface heat fluxes. In the LES experiments shown in Figure 2, the wind speed ranges between 5 and 15 ms^{-1}, the surface wave height varies from 0.5 to 4 m while the dominant wave length is kept at 60 m. The vertical velocity variance is a key measure of the turbulence field and represents the amount of kinetic energy available for mixing the water column. As wave forcing is added and La_t decreases, it becomes larger and reaches a maximum at a lower depth (Figure 2a). Figure 2b shows the depth-averaged (within the mixed layer) vertical velocity variances as a function of La_t. The far-right end point represents a pure shear turbulence case. The vertical velocity variance shows little variation until La_t drops below about 0.7. However, it increases rapidly as La_t further decreases. Figure 2b suggests a separation between the shear-dominated and Langmuir-dominated turbulence. Examination of other low-order turbulence statistics reveals an ordering of velocity variances typical of shear-driven turbulence when La_t>0.7, i.e. $< u'^2 >$ (downwind) **>** $< v'^2 >$(crosswind) **>** $< w'^2 >$(vertical). On the other hand, an ordering of $< v'^2 >$(crosswind) **>** $< w'^2 >$(vertical) **>** $< u'^2 >$ (downwind) appears when La_t<0.7, which is a signature of Langmuir turbulence. There are also distinctive differences in the mean velocity profiles. Shear turbulence tends to exhibit larger shear whereas Langmuir turbulence shows a more-uniform velocity profile in the mixed layer, indicating a more efficient vertical momentum transfer. These results are preliminary but convince us that a small set of distinguishing flow metrics does exist to characterize the turbulence field. We plan to compare these results with the observational data collected from the CBLAST experiments.

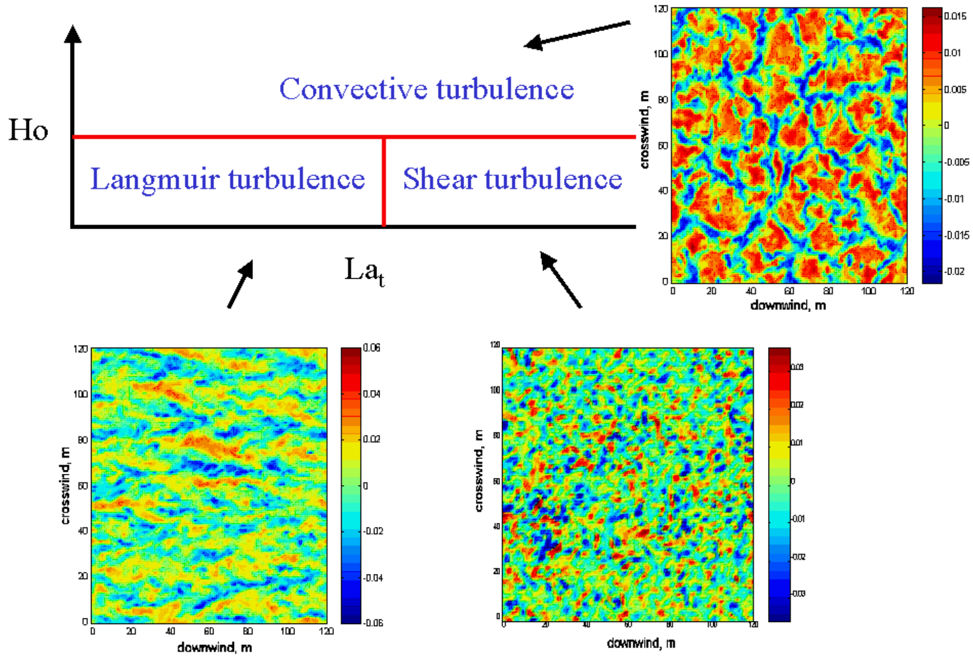

Figure 3. A regime diagram to differentiate convective, shear and Langmuir turbulence in the ocean surface boundary layer. One goal of our process studies is to construct such a diagram that can help interpret turbulence measurements in the upper ocean.

Given these preliminary model results, we anticipate that Langmuir turbulence will dominate the turbulence field if $Ho<O(1)$ and La_t is less than about 1. Similarly, shear turbulence will likely dominate if La_t is large and Ho is small. When Ho is large, or the Monin-Obukov length is much smaller than the mixed-layer depth, however, convective turbulence is expected to dominate regardless of the values of La_t. By exploring the parameter space, we hope to construct a regime diagram in Ho – La_t space that can differentiate shear-, wave- and buoyancy-driven turbulence over a wide range of surface forcing conditions. Our next step is to model these eddies in stratified water and investigate how they erode the stratification and cause the deepening of the mixed layer.

IMPACT/APPLICATIONS

Our modeling investigations into the upper-ocean turbulence dynamics will contribute to a better understanding of air-sea interaction and help interpret CLBAST field observations.

TRANSITIONS

None.

RELATED PROJECTS

We collaborate with Bob Weller, John Trowbridge and Jim Edson on interpreting data from CBLAST-Low experiments and Eric D’Asaro on interpreting data from CBLAST-Hurricane experiments.